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THE EFFECT OF A FREE GAS SATURATION ON THE SWEEP EFFICIENCY OF AN ISOLATED INVERTED FIVE-SPOT

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

CHEMICAL AND PETROLEUM ENGINEERING DEPARTMENT

by

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ABSTRACT

The objective of the research conducted and presented herein was to determine the effect of a pre-established free gas saturation on the sweep efficiency of an isolated inverted five-spot well pattern. The investigation concluded that the ultimate recovery of an isolated inverted five-spot may be slightly increased by establishing a free gas saturation prior to water flooding; however, of more significance is the extreme deviation of the pattern's performance after water breakthrough from that commonly obtained from developed well patterns, e.g., developed five-spot and developed seven-spot patterns: the rapid "water-out" characteristic common to both linear floods and floods conducted in developed well patterns was not evidenced in the isolated inverted five-spot. Instead, the wells continued to produce oil long after breakthrough until ultimate areal sweep efficiencies of four, five, and six hundred percent were obtained prior to the water-oil ratio becoming excessive.

The investigation further noted that these large areal sweep efficiencies could only be obtained if fill-up of the reservoir's indigenous gas saturation was obtained prior to breakthrough; otherwise, the rapid "water-out" characteristic common to linear floods and floods conducted in developed well patterns would prevail.

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INTRODUCTION

In the field of secondary recovery there has been much research into the areal sweep characteristics of various well patterns, and many investigations have studied the effect of a free gas saturation on the displacement characteristics of long cores, however, there has been little published literature on the behavior of an isolated inverted five-spot well pattern; hence, it is the object of this masterate dissertation to discuss the results of an investigation into the effect of a free gas saturation on the areal sweep efficiency of an isolated inverted five-spot.

In order to study the effect of a gas saturation it was necessary to construct a sand model rather than resort to an analogous approach such as a potentiometric model which would have simplified the problem somewhat, but which could not resolve the effect of a gas saturation. The model consisted of a half inch layer of uniformly packed unconsolidated Ottawa sand contained within two sheets of transparent, one-half inch thick, lucite five feet square and sealed on all four sides (Figure 1). The inverted five-spot pattern was centered in the model with twelve inches between the center injection well and each of the four producing wells such that the area contained within the five-spot (two square feet) was relatively small compared

to the total area of the model (twenty-five square feet) thus reducing the boundary effects in order that the model would behave similarly to that of an infinite reservoir. Pressure regulating apparatus, and oil, gas, and water measuring devices were employed to maintain rigid control over the experiments conducted on the model. A butane-iso-octane mixture was used to simulate a natural crude because of the ability to control its pressure - volume characteristics at the sub-atmospheric pressures employed throughout the experiments.

Prior to the direct use of the inverted five-spot model a number of preliminary experiments were conducted on a long core of unconsolidated Ottawa sand for the purpose of obtaining the basic sand, oil, and water properties of the system relevant to the evaluation of the performance of the larger three dimensional isolated inverted five-spot model. The effect of operational variables, e.g., rate and pressure, on the reproducibility of results were investigated, and an experimental procedure was developed for use on the larger model. The effect of a free gas saturation on the displacement efficiency of the long core was also studied (Figure 3) for possible explanation of the behavior of the larger model.

Upon development of a sound experimental procedure, experiments were conducted on the inverted five-spot model which were directed towards determining the recovery to breakthrough and thereafter until an arbitrary limiting water-oil ratio of 20:1 was obtained. The floods were conducted with and without a gas phase present in the model; the gas phase being established by reducing the pressure on the model such

that gas evolved from the saturated butane-iso-octane mixture.

A brief theoretical analysis of the problem is presented which concludes the futility of an analytical solution in favor of empirical treatment. The design of the apparatus and the development of the operating procedure is included, which is followed by a chronological description of the experiments conducted on both the long core and the inverted five-spot model. The observations and the results are then discussed, followed by the general conclusions of the investigation.

THEORETICAL ANALYSIS

I General

The possibility of predicting the performance of an isolated inverted five-spot by an analytical method was investigated in hope that the results obtained from the experimental model could be verified. A method was developed wherein the pressure distribution throughout the reservoir could be calculated and the progression at the flood front with time solved by a graphical procedure; however, the development of the pressure distribution would be a lengthy and tedious process and the eventual solution would be restricted to a system of unity mobility ratio. The determination of the pressure distribution could be expedited if the fluid within the reservoir were assumed incompressible, in which case the general pressure distribution equation would be somewhat simplified. It would also be possible to determine the pressure distribution through the use of a potentiometric model since an electric potential is directly comparable to pressure; however, unlike the fluid flow problem the compressibility of electricity is zero, and hence the same simplifying assumption would be inherent in the solution.

The introduction of a gas phase immediately invalidates the above methods of determining the pressure distribution throughout the inverted five-spot model for the same reason that limits the methods to a system of unity mobility ratio; i.e., the methods are based on the application of the superposition principle in solving the general La Place equation; the superposition principle is in turn a consequence

of the linear nature of the La Place equation and the introduction of mobility as a function of position would render the La Place equation non-linear.

It was thereby concluded that a general analytical method for predicting the performance of the inverted five-spot model was outside the scope of this dissertation; however, a brief description of the theory and the procedure to be employed in solving the limiting case of unity mobility ratio is presented herewith.

II Limiting Case - Unity Mobility Ratio

The following derivation of an analytical solution to the performance of an isolated inverted five-spot is included to stress the complexity of an analytical solution, the inherent simplifying assumptions, and hence the relative simplicity of an emperical solution obtained from an experimental model.

Theory - Incompressible Fluid

Considering a reservoir containing an incompressible fluid the law of continuity states that in every closed region in the reservoir the flow into the region must equal the flow out of the region. If the flow is considered moving with a velocity V in the x direction, the law of continuity may be expressed by the equation:

$$\frac{\partial V}{\partial x} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

By a more general argument considering a three dimensional system the general equation of continuity for incompressible fluids may be expressed by the equation:

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

Introducing Darcy's Law which relates the velocity of flow in the x direction (V_x) to the pressure drop per unit length $\left(\frac{\partial P}{\partial x}\right)$, the viscosity of the flowing fluid (v), and the permeability of the porous media (k) by the relationship

$$V_x = -\frac{k}{v}\cdot\frac{\partial P}{\partial x}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3$$

the equation of continuity takes the form:

$$\frac{\partial\left(\frac{k_x}{v}\cdot\frac{P}{x}\right)}{\partial x} + \frac{\partial\left(\frac{k_y}{v}\cdot\frac{P}{y}\right)}{\partial y} + \frac{\partial\left(\frac{k_z}{v}\cdot\frac{P}{z}\right)}{\partial z} = 0 \quad \ldots\ldots \; 4$$

If $\frac{k}{v}$ (referred to as the "mobility") is not a function of x, y, and z, i.e., the mobility of the system is not a function of position, Equation 4 becomes the general La Place Equation:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 5$$

There are many solutions to the La Place Equation; the importance of a particular solution lying in its relation to the physical problem in question. Through application of the superposition principle, which states that the reduction of pressure at any point in a reservoir is the algebraic sum of the pressure reductions caused by each well in a system, and that each well acts independently in producing its contribution to the pressure reduction at a point, Bruce (Equation 21, Part 1A)[1] has shown that a general solution to the La Place Equation for predicting the pressure distribution within a reservoir containing N wells may be expressed by the equation:

$$P_N = P_e + \sum_{j=1}^{N} \frac{q_j v}{2\pi kb} \ln \frac{r_j}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 6$$

where P_e is the pressure at some large radius $r = R$, b is the thickness of the formation, q_j is the production rate of the "jth well", and P_N is the pressure at a point N which is a distance r_j from the "jth well".

Through a lengthy number of calculations Equation 6 may be utilized in determining the pressure distribution throughout an isolated inverted five-spot.

Theory - Compressible Fluid

The introduction of compressibility into the problem of flow through a porous media introduces a time (t) rate of change of mass within the system, which changes the basic La Place differential equation to the general diffusivity equation:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2} = \frac{1}{K} \cdot \frac{\partial P}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots \quad 7$$

where K has been related to the homogeneous media's permeability (k), the viscosity of the fluid (v), the porosity of the media (f), and the compressibility of the homogeneous fluid (c) by the relationship

$$K = \frac{k}{vcf} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 8$$

The diffusivity equation states that the net mass flux, per unit time, through an infinitesimal volume element of a fluid system is equal to the free volume of the element multiplied by the rate of change of the fluid density within it. Because of the linearity of the diffusivity equation the superposition principle still holds and a general solution presented by Bruce (Equation 99, Part 1A)[1] may be employed to determine the pressure distribution throughout an

isolated inverted five-spot assuming a compressible fluid:

$$P_N = P_e + \frac{v}{4\pi kb} \sum_{j=1}^{N} E_i \left(- \frac{r_j^2}{4Kt} \right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 9$$

Although Equation 9 could be solved entirely analytically a more practical approach would be to plot the well system to scale, measure $r_1 \ldots r_5$ (N = 5 for the inverted five-spot) and look up the values of the $E_i(-z)$ function.* As steady state conditions are approached, i.e., time t approaches infinity, it might be noted that Equation 9 reduces itself to the case of zero compressibility (Equation 6).

Once the pressure distribution was established streamlines could be constructed from the injection well to the four producing wells; each streamline being drawn perpendicular to every iso-potential line it crosses. At any point on a given streamline the advance of a particle would be proportional to the average potential gradient in the direction of advance. The pressure gradient could be obtained graphically by measuring along the streamline the distance between successive iso-potentials and dividing the difference of potentials between these iso-potentials by the distance between them. Then after a chosen time interval, Δt, the distance, ΔS, that a particle had

---

* The $E_i(-z)$ function may be found tabulated in the British Association Tables for the $E_i(-z)$ Function, the Janke and Emde Tables, and/or in the W.P.A. Tables.

moved along a streamline could be given by:

$$\Delta S = \frac{\Delta P}{\Delta S} \cdot \frac{k}{f_V} \Delta t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 10$$

The subsequent position of a flood front could thus be determined graphically. Until breakthrough the oil production would be equal to the injected water; thereafter, the oil production would be equal to the areal sweep efficiency and could be determined by the use of a planimeter.

It is thus shown how the performance of an isolated inverted five-spot would be predicted analytically; however, because this approach is limited to a system of unity mobility ratio, it could not be employed as a means of verifying the empirical results obtained from the experiments on the isolated inverted five-spot model.

EMPIRICAL ANALYSIS

I Design of Apparatus

Having abandoned the analytical approach to the solution of the behavior of an isolated inverted five-spot in favor of an empirical approach the design of the apparatus was given careful consideration. It was decided to build an unconsolidated sand model to simulate an inverted five-spot isolated in an effectively infinite reservoir.

The model was built employing unconsolidated Ottawa sand as a porous media contained between two five foot square sheets of one-half inch thick lucite. The model was sealed on all four sides with a half inch thick strip of lucite which gave the model a uniform sand thickness

SCHEMATIC DIAGRAM OF APPARATUS

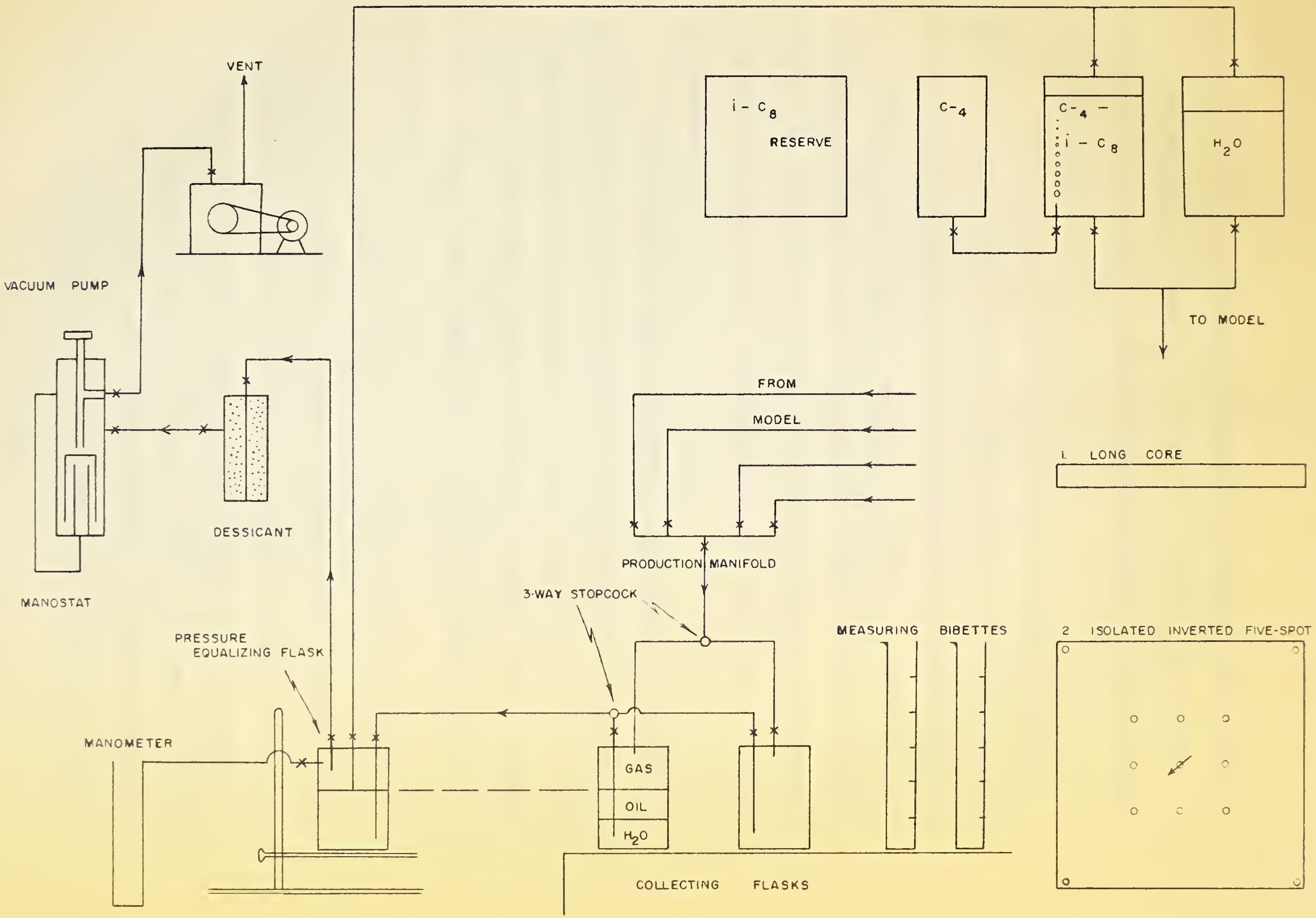


FIG 1

of one-half inch. The principle behind the relatively thin layer of sand was to reduce the effects of gravity as well as to maintain translucency such that a lighting apparatus could be used to visually trace the progression of the flood front.

The model was filled with sand after assembly; the sand being poured into place through a small aperture in one corner of the model. As the sand poured into place the model was gently "tapped", which resulted in an apparent homogeneous permeability distribution throughout the model as well as producing a slight internal pressure between the sand and the lucite. This slight internal pressure was necessary to prevent fluid from by-passing the sand along the lucite-sand contact.

The simulated "wells" employed in the model were machined out of brass, and were designed such that they would (1) not "sand-off", (2) not effect un-uniform production and/or injection characteristics, (3) aid in maintaining rigidity throughout the model, and (4) incorporate a spacing device which would help ensure a uniform sand thickness.

The inverted five-spot pattern was centered in the model with twelve inches between the center injection well and each of the four producing wells such that the area contained within the five-spot (two square feet) was relatively small compared to the total area of the model (25 square feet), thus reducing the boundary effects in order that the model would behave similarly to that of an infinite reservoir. Eight "wells" other than those constituting the five-spot

were employed in the model to help maintain rigidity and uniform sand thickness throughout the model as well as to facilitate the re-establishment of a uniform fluid saturation throughout the model after each run.

In order to prevent parting of the lucite-sand interface sub-atmospheric pressures were maintained within the model throughout all the experiments. A cartesian-type manostat apparatus was used to regulate the pressures imposed on the system. The manostat made it possible to maintain a constant pressure differential over the model regardless of the volume of the effluent. The pressure regulating apparatus was so constructed that the oil and water production from the model could be measured without having to "shut-in" the model.

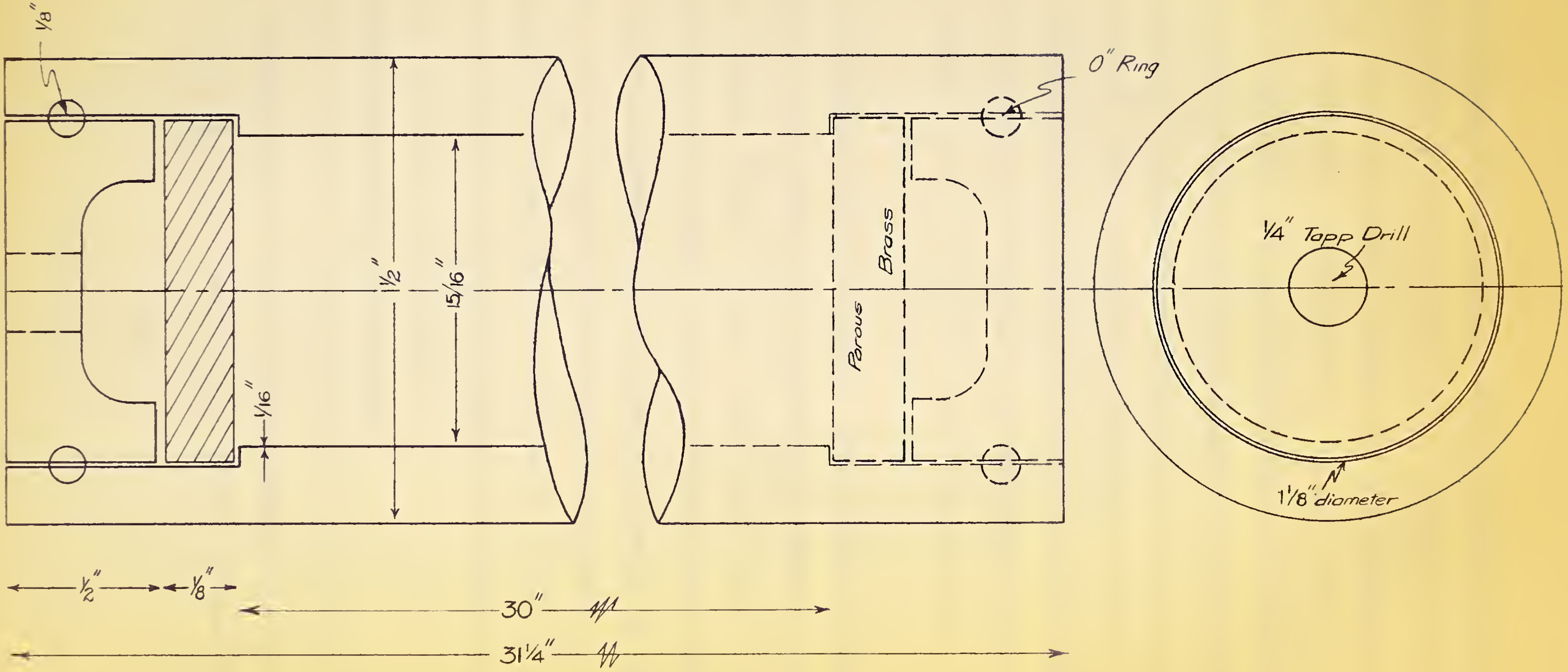
The fluid chosen to simulate a natural crude was a butane-iso-octane system because of its favorable pressure-volume behavior at the sub-atmospheric pressures employed throughout the experiments. A pure system was desirable in order that the equilibrium of the system could be changed at will to a somewhat predictable equilibrium, and one which could be duplicated thus facilitating the reproducibility of results.

PRELIMINARY EXPERIMENTS ON LONG CORE

I General

Prior to the direct use of the inverted five-spot model a number of preliminary experiments were conducted on a long core of unconsolidated Ottawa sand for the purpose of obtaining the basic

DIAGRAM OF LONG CORE



properties of the sand-oil-water system relevant to the evaluation of the performance of the larger three dimensional isolated inverted five-spot model. These experiments included the determination of the sand's porosity, irreducible water saturation (connate water), residual oil saturation, permeability, and the determination of the mobility ratio of the system. The experiments were extended to the determination of the effect of a pre-established free gas saturation on the displacement efficiency of the long core; the objective being to obtain data which could be used in explaining the behavior of the larger model. The preliminary experiments also served in the development of an experimental procedure to be used on the larger five-spot model.

II Porosity

In determining the porosity of the unconsolidated Ottawa sand the dimensions of the empty core were carefully measured. The empty core was weighed, filled with water, and weighed again to determine the total volume of the core. The core was emptied of water, packed with sand, and weighed to determine the sand content of the core. The sand-packed core was then filled with water and weighed; the additional weight representing the pore volume of the core. Dividing the pore volume of the core by the total volume of the core resulted in a porosity of 34.2 percent (Enclosure 1).

III Connate Water and Residual Oil Saturation

A mixture of butane-iso-octane saturated at an absolute pressure of 25 inches of mercury was displaced through the water-saturated core until the water content of the effluent was negligible,

and the irreducible water saturation was noted. The oil mixture was subsequently displaced from the core with water until the oil content of the effluent was negligible, and the residual oil saturation was noted.

The core was then flushed with oil until the water content of the effluent was negligible and the resultant residual water saturation determined. It was noted that the residual water saturation obtained at this point was identically equal to the irreducible water saturation obtained initially. It was concluded that consistent initial oil and water saturations could be established within the core after each run without having to change or clean the sand.

The displacement efficiency of the long core to breakthrough and thereafter to the residual oil saturation was then studied. The core was noted to "water-out" very rapidly after breakthrough until the oil content of the effluent was negligible. After twelve such runs it was noted that the residual oil saturation was invariably constant at 11.2 ± 2.0 percent, and the re-established irreducible water saturation was constant at 22.0 ± 2.0 percent.

IV Mobility Ratio

The mobility ratio may be defined as the ratio of the sum of the mobilities of the fluids moving ahead of a displacement front to the sum of the mobilities of the fluids moving behind the front. For the oil-water system considered herein the fluids moving ahead of the front may be reduced to the flow of oil (denoted by the subscript $_o$), and the fluids moving behind the front may be reduced to the flow of water (denoted by the subscript $_w$). The mobility ratio may be sub-

sequently expressed by the following equation:

$$J = \frac{k_w}{v_w} \cdot \frac{v_o}{k_o} \quad \text{. . . . .} \quad 11$$

Introspection of the general Darcy[2] equation and its relationship to mobility will reveal that the mobility ratio of the system herein may be determined by comparing the ability of the long core to transmit water to the ability of the core to transmit oil.

The irreducible water saturation was established within the core thus simulating the fluid saturation ahead of the displacement front. Maintaining a set pressure differential across the core the time required to transmit a definite volume of oil (100 cc) through the core was noted. The fluid saturation behind the front was then simulated by displacing the oil from the core until the oil content of the effluent was negligible. Maintaining the same pressure differential across the core, the time required to transmit 100 cc of water was noted. The ratio of the two times, which is effectively the mobility ratio of the system, was found to be 0.423.

V Permeability

It will subsequently be shown that it was necessary to obtain the permeability of the unconsolidated Ottawa sand (20:30 mesh) in order to approximate the minimum rate of flow required to reduce the capillary effects on the displacement efficiency of the five-spot model to a negligible value. The permeability was, therefore, determined by a direct application of Darcy's law and found to be 778 darcies (Enclosure 1), which is in good agreement with previously reported

data[2] on unconsolidated sands.

VI Critical Scaling Coefficient

The theory of water-oil displacement may be employed to show how the displacement efficiency of a given two or three dimensional system is injection-rate sensitive because of the inherent effect of capillary pressure.[3] Increasing the injection rate has an increasing effect on the displacement efficiency until a critical injection rate is reached, above which the capillary effect is rendered negligible. In order that variations in injection rate did not effect the displacement efficiency of the experiments conducted on the long core and the isolated inverted five-spot model the critical injection rates were approximated employing empirical data from the literature. The injection rates employed throughout the experiments were then kept in excess of the calculated criticals.

Rapoport et al[4] related the displacement efficiency of a linear system to the variables which determine the magnitude of the capillary effect expressed by the term

$$C_1 = Luv_w \quad \dots\dots\dots\dots\dots\dots\dots\dots \quad 12$$

where C_1 is referred to as the scaling coefficient, L is the length of the system (cm), u is the injection rate per unit cross sectional area $\left(\frac{cc/cm^2}{min}\right)$, and v_w is the viscosity of the water (cps). The authors found that the critical value of the scaling coefficient (abbreviated C.S.C. herein) was in the order of 5.0; hence the critical injection rate for the long core was determined by substituting the known values of L and v_w into Equation 12 and solved for u (Enclosure 1).

The calculation revealed that as long as the injection rate exceeded 0.314 cc per minute the capillary pressure effect would be negligible.

In a subsequent paper Rapoport et al[5] have further shown that for a three dimensional flood the displacement efficiency is no longer dependent upon the dimensions of the system but is dependent upon the permeability and the porosity of the porous media (k and ϕ respectively) and the oil-water interfacial tension (σ). The scaling coefficient may now be expressed by the relationship

$$C_2 = \frac{q v_w}{\sigma (k\phi)^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 13$$

where q is the injection rate per unit sand thickness (barrels/day/ft.). The units of σ, k and ϕ are dynes/cm, millidarcies, and percent respectively. The critical scaling coefficient for the five-spot considered herein was approximated at 3.5×10^{-3} upon considering the empirical critical scaling coefficients obtained by the authors for 15 different water flood tests. The critical injection rate for the isolated inverted five-spot model was then calculated by solving Equation 13 for q. The resultant 193 cc per minute was found to be slightly less than the 212 cc per minute injection rate obtained when a 2.646 inch mercury head was imposed across the model. It was, therefore, concluded that the capillary effect could be maintained at a negligible value as long as the pressure differential was kept in excess of 2-1/2 inches of mercury across the model.

THE EFFECT OF A FREE GAS SATURATION ON THE DISPLACEMENT EFFICIENCY OF THE LONG CORE

I Procedure

After the displacement efficiency to breakthrough was positively established while flooding under no initial gas saturation, the displacement efficiency characteristics of the core for various pre-established gas saturations were studied. The core was prepared as before to simulate initial saturation conditions of water and oil and the pressure was reduced on the core below the saturation pressure of the butane-iso-octane mixture such that gas evolved from the oil. The gas effected a solution gas drive mechanism which resulted in a volume of oil being produced from the core. The volume of oil produced was assumed to represent the gas saturation of the core.* A gas saturation being established, water was injected into the core under constant pressure differential and the volume of oil displaced from the core until water "breakthrough" was noted. The sum of the oil produced prior to flooding and the oil recovered to breakthrough represented the ultimate oil recovery from the core.

II Results

The results of the tests conducted on the long core are tabulated in the Appendix (Enclosure 2) and are graphically illustrated

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* This assumption may be calculated for the conditions imposed on the system and found to contain an inherent error of less than 3 percent.

by Figure 3, which presents the displacement efficiency of the core versus the oil production prior to flooding; the latter being essentially equivalent to the gas saturation prior to flooding. The relationship shows that for the operating conditions employed throughout the experiments a maximum ultimate recovery was obtained by establishing a gas saturation of approximately 8 percent prior to flooding.

Included in the relationship are two anomalous points represented by the symbol ⊙ which are the displacement efficiencies resulting from a variation in the pressure differential imposed on the core during flooding, i.e., the pressure drop across the core was increased from 3 inches of mercury to 4 inches of mercury for these two runs. The obvious result was that the residual gas saturation behind the flood front was decreased because the higher injection pressure put more gas back into solution; and hence the ultimate recovery was slightly lower than that obtained with the lower injection pressure. The significance of these points lies in their exemplifying the critical dependency of the pressure at the water-oil front, and hence the injection pressure, on the increase in ultimate recovery effected by establishing a gas saturation prior to flooding.

It may, therefore, be concluded that the increase in ultimate recovery effected by establishing a free gas saturation prior to flooding is greatly affected by the pressure imposed on the free gas at the water-oil front and hence the injection pressure. This is a result of gas-oil equilibrium and its relationship with

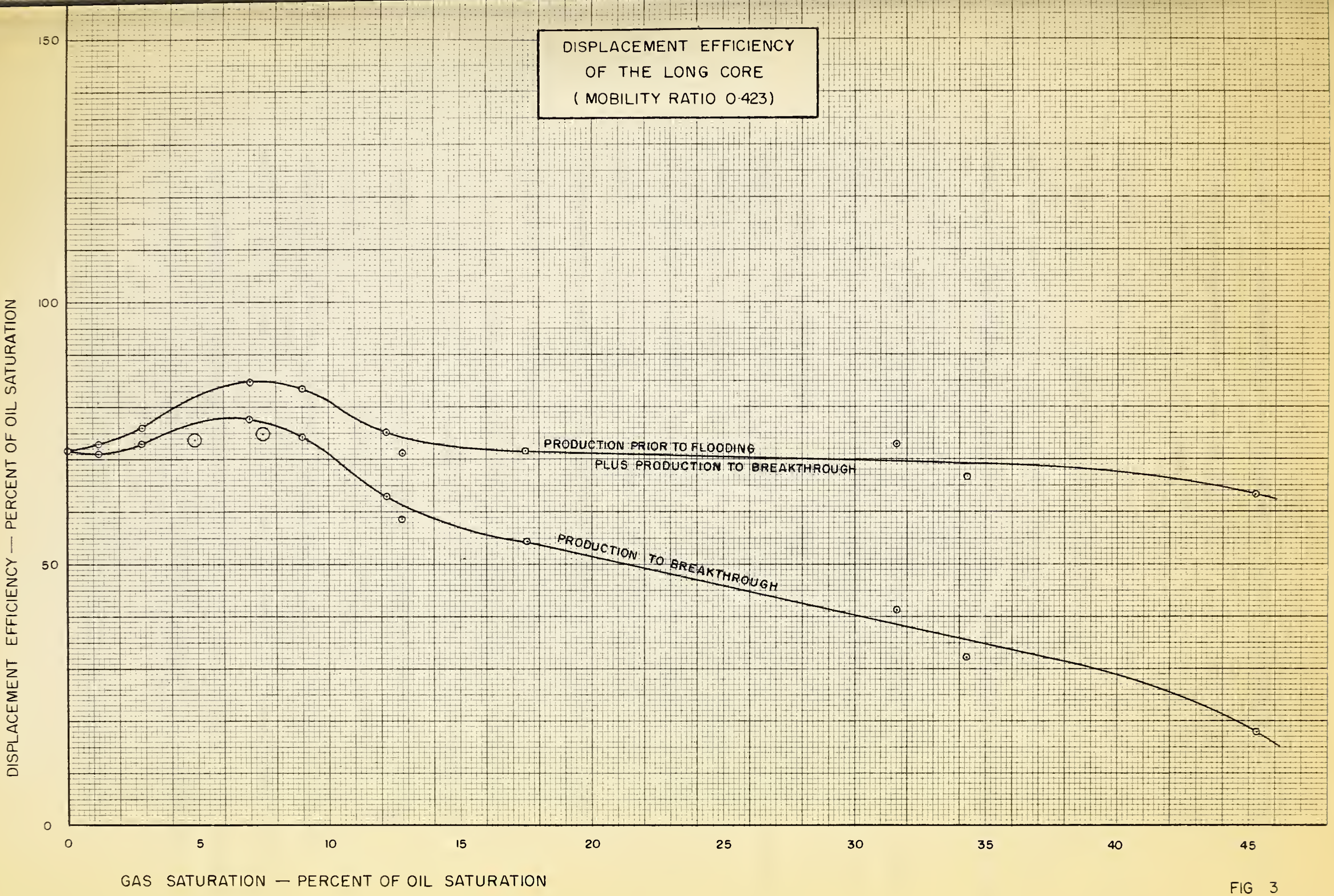

DISPLACEMENT EFFICIENCY
OF THE LONG CORE
(MOBILITY RATIO 0·423)
PRODUCTION PRIOR TO FLOODING
PLUS PRODUCTION TO BREAKTHROUGH
PRODUCTION TO BREAKTHROUGH
DISPLACEMENT EFFICIENCY — PERCENT OF OIL SATURATION
150
100
50
0
0
5
10
15
20
25
30
35
40
45
GAS SATURATION — PERCENT OF OIL SATURATION

FIG 3

pressure: the greater the pressure imposed on the free gas by the advancing flood front the greater will be the amount of gas which goes back into solution, and the smaller will be the increase in ultimate recovery effected by establishing a free gas saturation prior to flooding. It is conceivable how an extremely high injection pressure could reduce the residual gas saturation behind the flood front to a negligible amount and hence reap no benefits from establishing a gas saturation prior to flooding.

It was concluded at this time that an increase in ultimate recovery may be effected by establishing a free gas saturation prior to flooding, however, the exact increase is dependent upon too many variables to arrive at a generalized relationship. The gas saturation at which the maximum oil recovery may be obtained depends upon all the physical characteristics of the reservoir; it depends upon the molecular composition of the reservoir fluid and its related pressure-volume-temperature behavior; and, as has been shown, it depends greatly upon the pressure distribution imposed on the reservoir.

In a three dimensional reservoir, such as an isolated inverted five-spot, the residual gas saturation left behind the advancing flood front becomes a more complex problem. The pressure distribution in such a reservoir is a transient function varying with time such that the residual gas saturation left behind the water bank, which is essentially equal to the increase in ultimate recovery over flooding without a pre-established gas saturation, varies throughout the flood. It is conceivable how the residual gas saturation in

the proximity of the injection well may be reduced to a negligible value because of the high sand-free injection pressure, whereas the residual gas saturation at a distance far removed from the injection well could be quite significant.

At this point the preliminary experiments on the long core were concluded and the three dimensional model connected to the pressure regulating apparatus for analyzing the behavior of the isolated inverted five-spot.

ISOLATED INVERTED FIVE-SPOT

I Procedure

The isolated inverted five-spot model, being mounted according to the schematic diagram of Figure 1, was displaced with several pore volumes of water; the water being injected in the center well and produced through the remaining twelve wells to ensure complete fill-up of the pore space. The saturated reservoir crude, represented by a butane-iso-octane mixture saturated at 25 inches of mercury, was then injected into the center well and the water content of the model reduced to the "irreducible minimum" by passing several pore volumes of the butane-iso-octane mixture through the model until the water content of the effluent was negligible. The volume of water displaced from the model was 7863 cc which corresponded to an irreducible water saturation of 21 percent. This was comparable to the 22 percent irreducible water saturation obtained from the preliminary experiments conducted on the long core (Enclosure 1).

Once the irreducible water saturation was established the injection of the butane-iso-octane mixture was discontinued. The pressure was then slowly reduced on the model to the saturation pressure of the mixture (25 inches of mercury) where it was held constant until the pressure distribution throughout the model equalized. The model at this point represented "original conditions" for all future runs: effectively an infinite oil reservoir at its saturation pressure.

The objective of the succeeding experiments was to determine the amount of recoverable oil to breakthrough and thereafter to an arbitrary limiting water-oil ratio for (1) a simulated undersaturated reservoir (no free gas present) and (2) a simulated saturated reservoir exhibiting a definite interstitial gas saturation. If the establishment of a free gas saturation prior to flooding was to increase the ultimate recovery from the model, it was hoped that the saturation resulting in the optimum recovery could be determined. The procedure could be briefly summarized as follows:

1) The model was flooded at the "Original Conditions" recording the recovery to breakthrough and thereafter.
2) Re-establishing the "Original Conditions" in the model the pressure was reduced to a pre-set value and the volume of oil produced by the resultant "solution gas drive mechanism" recorded. (The oil volume represented the gas saturation in the reservoir at the final stabilized pressure.)

3) The model was then flooded and the effect of the pre-established gas saturation on the recovery to breakthrough and thereafter noted.

4) "Original conditions" were re-established and the pressure reduced on the model such that a different volume of oil was produced prior to flooding. The model was flooded and the effect of the different pre-established gas saturation on the recovery to breakthrough and thereafter was noted.

5) Step (4) was repeated several times such that a general relationship was developed relating the sweep efficiency to the production prior to flooding; the production prior to flooding being essentially equivalent to the free gas saturation.

In Step (1) of the above procedure a constant pressure of 25 inches of mercury (absolute) was maintained on the four corner producing wells of the isolated inverted five-spot model and water was injected into the center well at an approximately constant pressure head of three feet of water (2.646 inches of mercury). It was necessary that the injection pressure be maintained less than atmospheric at all times to prevent the lucite from parting with the unconsolidated sand within the model.

In order that the forward advance of the flood front could be visualized, the initial 10 cc of injection water contained a water

soluble green dye. The coloured water was readily discernable in the transparent "flow-lines" from the producing wells; and hence the uniformity of breakthrough in the four producing wells of the model was easily noted. For the various floods conducted on the model all the wells attained breakthrough within a 25 cc production range, and the wells did not exhibit any tendency to breakthrough in a definite order each time, which would have suggested a non-uniform media.

Once breakthrough occurred in all four wells the well effluent was switched to a different production flask and the production to breakthrough measured in a graduated cylinder. The flood was continued after breakthrough recording the oil and water production in production increments of 500 to 1000 cc (Enclosures 3 to 8 inclusive) until a producing water-oil ratio of approximately 20:1 was obtained (an arbitrary economic limiting water-oil ratio). The progression of the flood front was visually noted, and the position of the flood front at various stages of the flood traced onto the lucite with chalk such that a typical flood progression could be illustrated as in Figure 4.

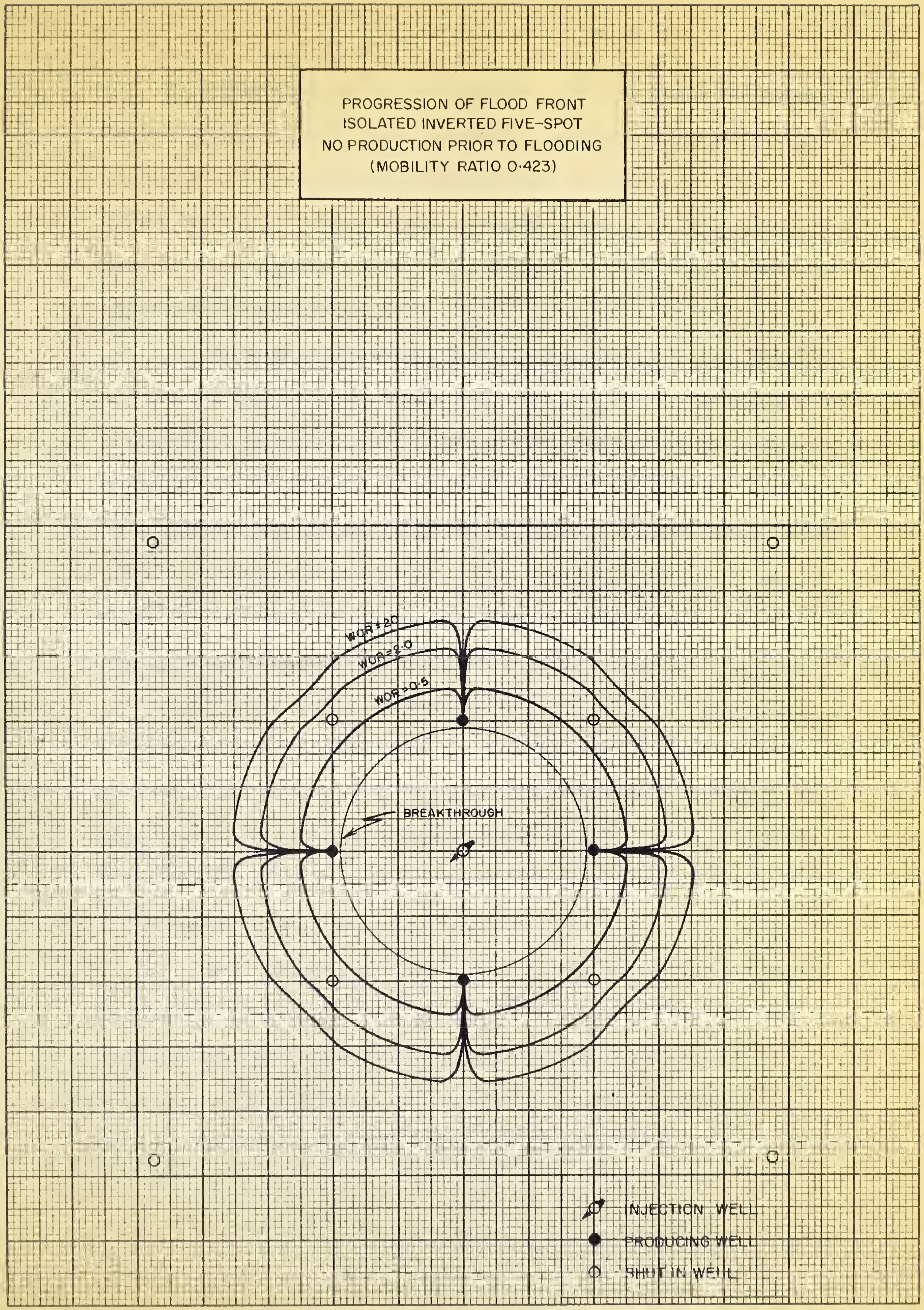
The development of a generalized relationship relating sweep efficiency to pre-established gas saturation required that the production data obtained from the model be converted to dimensionless terms such that the resultant relationship could be readily employed to predict the performance of an isolated inverted five-spot of any dimension. The areal sweep efficiency was expressed as a fraction

of the total volume of displaceable oil contained within the five-spot element (termed the "Displaceable Pore Volume" of the five-spot element), and was calculated knowing

1) the volume of the five-spot element (2361 cc),
2) the porosity of the sand (34.2 percent),
3) the connate water saturation of the sand (22.0 percent), and
4) the residual oil saturation left behind the waterbank (11.2 percent of the total pore volume).

Hence for 100 percent areal sweep efficiency 1.0 displaceable pore volumes or 629.05 cc of oil had to be swept from the model.

Unlike the pre-established gas saturation within the linear core, which was assumed uniform throughout the length of the core and was consequently expressed as a percent of the total pore volume occupied by oil, the expression of the pre-established gas saturation within the effectively infinite three dimensional model as a percent of either total pore volume or total pore volume occupied by oil was inapplicable. This is a consequence of the assumed effective boundlessness of the model, the resultant assumed ever present pressure gradient, and hence an assumed gradient in the gas saturation. Because of the identity between pre-established gas saturation and production prior to flooding the areal sweep efficiency was directly related to the production prior to flooding; the production prior to flooding being expressed in the same dimensionless units as the areal sweep efficiency, viz., displaceable pore volumes.



PROGRESSION OF FLOOD FRONT
ISOLATED INVERTED FIVE-SPOT
NO PRODUCTION PRIOR TO FLOODING
(MOBILITY RATIO 0·423)

FIG. 4

After flooding to the limiting water-oil ratio the model was restored to "original conditions" by displacing the water from the model to the irreducible minimum water saturation with the butane-iso-octane mixture saturated at 25 inches of mercury (absolute). Once the water content of the well effluent was negligible the water saturation was assumed to have reached the irreducible minimum.

The vacuum regulating apparatus was then set such that the pressure of the model was slowly reduced from its saturation pressure (25 inches of mercury) to 24 inches of mercury; the pressure regulating apparatus being connected to the five wells of the five-spot pattern. The model was held at this pressure until the effluence of oil from the five producing wells was negligible. The production to this point (219 cc) represented an established gas saturation within the model prior to flooding.

Water was then injected in the center well maintaining a constant drawdown pressure on the producing wells equal to the reservoir pressure prior to flooding (24.08 inches of mercury). The recovery to breakthrough was recorded as well as the additional recovery thereafter to a producing water-oil ratio of 20:1.

II Observations and Results

Upon flooding the model at "original conditions", i.e., no production prior to flooding, 694 cc of oil were obtained at breakthrough, which represented an areal sweep efficiency of 110 percent. The production of oil continued with the proportion of water in the effluent slowly increasing (Enclosure 9). At a producing

water-oil ratio of 0.5:1 the areal sweep efficiency was noted to have increased to 305 percent. At a producing water-oil ratio of 1.0:1 the areal sweep efficiency had increased to 410 percent, and by the time an arbitrary limiting water-oil ratio of 20:1 was reached the areal sweep efficiency had increased to 655 percent. The model was then restored to "original conditions" and reflooded to check the performance of the first run. The production to breakthrough (692 cc) was well within the accuracy of the measuring equipment, and the production thereafter practically duplicated the first run. It was, therefore, concluded that the performance obtained for the flooding of the isolated inverted five-spot with no free gas saturation present was authentic.

Upon restoring the model to the "original conditions" and reducing the pressure to 24.08 inches of mercury 219 cc of oil were produced. Flooding the model recovered 612 cc of oil to breakthrough. The production thereafter essentially duplicated the production behavior after breakthrough for the flood with no production prior to flooding. The sum of the oil produced prior to flooding and that recovered during the flood prior to breakthrough (219 cc + 612 cc = 831 cc) was in excess of the oil recovered to breakthrough in the flood conducted at zero gas saturation by 137 cc. This additional recovery could be considered the increase in ultimate recovery obtained by establishing free gas saturation prior to flooding. Since the residual gas saturation behind the flood front has been shown to be directly dependent upon the water injection pressure, the increase effected by

establishing the gas saturation prior to flooding cannot be applied as a general increase-in-recovery factor; however, it may be generally concluded that an increase in ultimate recovery is possible by establishing a gas saturation prior to flooding.

After restoring the model to the original conditions and reducing the pressure to 23.21 inches of mercury 365 cc of oil were produced prior to flooding. Upon flooding 470 cc of oil were recovered to breakthrough. Thereafter the "watering-out" characteristics of the model closely resembled the previous floods.

The ultimate recovery at two other established gas saturations prior to flooding yielded recoveries just slightly in excess of that with no gas saturation present.

1 Production Prior to Flooding cc	2 Production to Breakthrough cc	3 Total Recovery to Breakthrough 1 + 2 cc
0	694	694
219	612	831
365	470	835
554	237	791

However, when the model was reduced to 21.02 inches of mercury and 944 cc of oil produced prior to flooding the flooding performance experienced an extreme deviation from previous runs: although the recovery to breakthrough (158 cc) was in line with that which was expected, the production thereafter deviated from the previous

behavior in that a very rapid water-out occurred. An areal sweep efficiency of only 95 percent was obtained at the limiting water-oil ratio of 20:1.

Restoring the model to the original conditions and conducting a flood at 20.07 inches of mercury (prior to which 1264 cc of oil were produced) resulted in an even lower ultimate areal sweep efficiency: 21.2 percent at breakthrough increasing to 35.0 percent at the limiting water-oil ratio of 20:1. At this point the experiments on the isolated inverted five-spot model were terminated.

III Discussion

The data of six different floods were assembled; five of which represented the flooding performance of the model with definite gas saturations present prior to flooding and one representing the model's performance with no gas saturation present prior to flooding. The data were tabulated (Enclosures 3 to 8 inclusive) and graphically illustrated (Enclosures 9 to 14 inclusive) such that the areal sweep efficiency could be graphically determined for any given instantaneous producing water-oil ratio.

A general relationship was then developed relating the areal sweep efficiency at different producing water-oil ratios to the volume of oil produced prior to flooding (Figure 5); the production prior to flooding being essentially equivalent to the gas saturation established within the model prior to flooding. It was observed that the areal sweep efficiency at any arbitrary limiting water-oil ratio was relatively independent of the volume of oil produced prior to

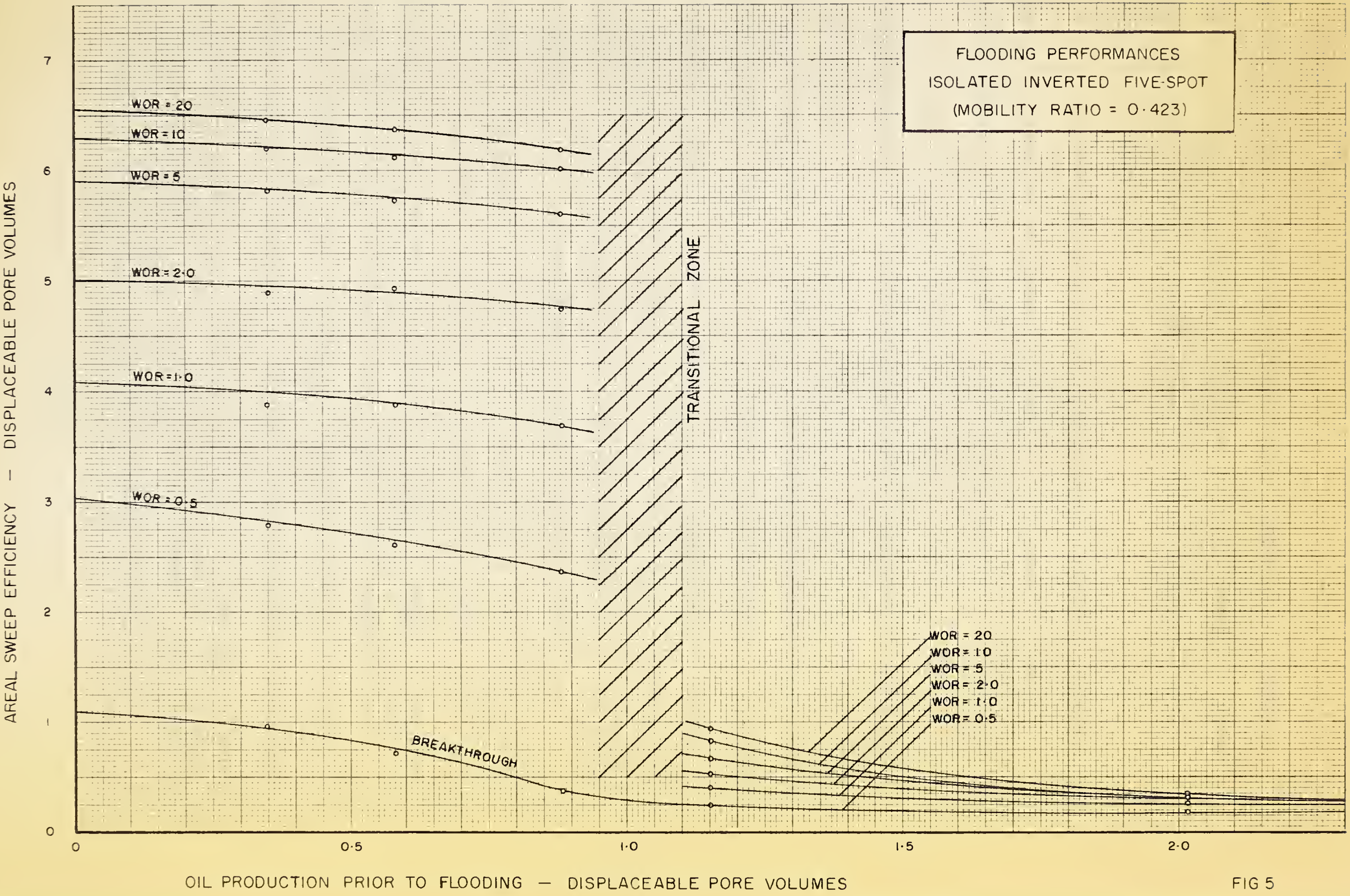

FLOODING PERFORMANCES
ISOLATED INVERTED FIVE-SPOT
(MOBILITY RATIO = 0·423)
WOR = 20
WOR = 10
WOR = 5
WOR = 2·0
WOR = 1·0
WOR = 0·5
BREAKTHROUGH
TRANSITIONAL ZONE
WOR = 20
WOR = 10
WOR = 5
WOR = 2·0
WOR = 1·0
WOR = 0·5
AREAL SWEEP EFFICIENCY — DISPLACEABLE PORE VOLUMES
0
1
2
3
4
5
6
7
0
0·5
1·0
1·5
2·0
OIL PRODUCTION PRIOR TO FLOODING — DISPLACEABLE PORE VOLUMES

FIG 5

flooding up to a pre-production range in the order of 1.0 displaceable pore volumes. If the model produced in excess of this critical range the model was noted to "water-out" very rapidly after water breakthrough was attained.

The production prior to flooding which initiates the rapid water-out phenomenon (hereinafter referred to as the "critical pre-production") may be related to what is hereinafter referred to as the "critical fill-up volume" of the model. If the residual gas saturation behind the waterbank, which is essentially equivalent to the increase in displacement efficiency effected by establishing a gas saturation prior to flooding, were assumed negligible the fill-up volume would be identically equal to the production prior to flooding. The critical fill-up volume would then be identically equal to the critical pre-production, which would be equal to the areal sweep efficiency to breakthrough effected when there is no production prior to flooding, i.e., 1.10 displaceable pore volumes. However, as has been shown by the experiments on the long core, the residual gas saturation behind the front is not necessarily negligible, but depending upon the pressure distribution within the model throughout the flood, may occupy a definite pore volume. Hence the fill-up volume is equal to the pre-production less the volume of residual gas left behind the front. The critical fill-up volume of the model is, therefore, slightly less than the critical pre-production, which in turn is constant at 1.10 displaceable pore volumes. The transition zone, beyond which the rapid water-out phenomena prevails, was

therefore assumed to lie in the approximate pre-production interval 1.0 to 1.10 displaceable pore volumes. The exact flooding behavior in the transition zone was not investigated but would be a good subject for a subsequent study.

The extreme deviation in the performance after breakthrough of the isolated inverted five-spot compared to the developed five-spot may be directly attributed to the significant difference in the pressure distribution of the two patterns. Similarly the requisite that fill-up occur prior to breakthrough in order to prevent rapid water-out is also a consequence of the character of the pressure distribution within the isolated inverted-five spot prior to fill-up, and after fill-up.

In relation to the pressure distribution within an isolated inverted five-spot prior to fill-up, Dalton et al[6] have shown how the behavior of an isolated inverted five-spot in the presence of a free gas is governed by the dimensionless pressure parameter

$$\pi = \frac{P_s - P_{wp}}{P_{wi} - P_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 14$$

where P_s is the static reservoir pressure, P_{wi} is the sand face injection pressure and P_{wp} is the flowing bottom hole pressure.

This pressure parameter expressing the ratio of the pressure drawdown at the producing wells to the pressure buildup at the injection well is defined as the "π ratio". It has been shown that the greater the π ratio, i.e., the greater is the drawdown pressure differential over the injection pressure differential, the greater

will be the amount of oil swept to the producing wells over that swept out into the surrounding reservoir. The significance lies in the competition of the producing wells and the surrounding reservoir for the flow of oil and water. The concept of the π ratio is only valid prior to fill-up since the pressure distribution within the reservoir thereafter is effectively independent of the drawdown and/or the injection pressures.

The flooding experiments conducted on the isolated inverted five-spot model in the presence of free gas operated at a π ratio of zero, i.e., the pressure difference between the producing wells and the static reservoir was zero. It may be seen how the recovery to breakthrough could have been increased had a drawdown been imposed on the producing wells. It is also conceivable that under an increased π ratio fill-up could occur at some period in the life of the flood after breakthrough which might result in the lower water-out characteristics common to the floods which experienced fill-up prior to breakthrough.

The performance of the isolated inverted five-spot operating in the presence of a free gas and with a π ratio other than zero poses a slightly different aspect of the problem resolved herein, and is a good subject for a subsequent study.

CONCLUSIONS

Upon examination of the results of the flooding tests conducted on the isolated inverted five-spot for various established gas saturations prior to flooding it was concluded that the ultimate recovery from such a well pattern may be increased by establishing a gas saturation prior to flooding as long as "fill-up" is obtained prior to water breakthrough.

It is further concluded that the rapid "water-out" characteristic common to linear floods and floods conducted in developed well patterns is not prevalent in the case of an isolated inverted five-spot. Instead, the producing water-oil ratio increases very slowly after breakthrough such that ultimate areal sweep efficiencies six times that at breakthrough are possible.

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APPENDIX

ENCLOSURE 1

Preliminary Experiments Conducted on the Long Core

1. Calculation of Porosity

Averaged weight of empty core	780.8 gm.
Averaged weight of packed core	1430.0 gm.
Averaged weight of water filled core	1156.6 gm.
Weight of water in core (core volume)	375.8 gm.
Averaged weight of saturated packed core	1559.7 gm.
Water content of core (pore volume)	128.4 gm.

Porosity:

$$\frac{128.4}{375.8} = 34.2 \text{ percent}$$

2. Calculation of Connate Water Saturation

Pore Volume of core (porosity calculation)	128.4 cc
Averaged volume of water displaced by oil	100.15 cc
Volume of irreducible water	28.25 cc

Connate water saturation:

$$\frac{28.25}{128.4} = 22.0 \text{ percent}$$

3. Calculation of Residual Oil Saturation

Pore Volume of core (porosity calculation)	128.4 cc
Averaged volume of water displaced by oil	100.15 cc
Averaged maximum oil displaced by water	85.75 cc
Volume of residual oil	14.40 cc

Residual oil saturation:

$$\frac{14.40}{128.4} = 11.2 \text{ percent}$$

4. Calculation of Mobility Ratio

Averaged time to flow 100 cc of water through core	188.0 sec.
Averaged time to flow 100 cc of oil through core	79.6 sec.

Mobility ratio:

$$\frac{79.6}{188.0} = 0.423$$

5. Calculation of Permeability[2]:

$$K = \frac{Qv_wL}{A\ (P_1 - P_2)}$$

$Q = 2.45\ \frac{cm^3}{sec}$ $v_w = 0.93$ cps @ 78°F

$L = 76.2$ cm $A = 4.45\ cm^2$

$P_1 - P_2 = 0.0501$ atmos.

$$K = \frac{(2.45)(0.93)(76.2)}{(4.45)(0.0501)}$$

$$= 778 \text{ darcies}$$

6. Critical Scaling Coefficient Relationship:

1. Linear Core[3]:

$$\text{C.S.C.} \doteq 5.0 = Luv_w$$

$v_w = 0.93$ cps @ 78°F $L = 76.2$ cm

$$\therefore\ u = \frac{5.0}{(76.2)(0.93)} = 0.0705\ \frac{cm^3}{cm^2} \cdot \frac{1}{min}$$

For cross-sectional area of $4.45\ cm^2$ the minimum throughput required would be:

$$u = 0.0705 \times 4.45 = 0.314\ \frac{cm^2}{min}$$

2. Isolated Inverted Five-Spot[5]:

$$\text{C.S.C.} \doteq 3.5 \times 10^{-3} = \frac{qv_w}{\sigma (k\phi)^{\frac{1}{2}}}$$

$v_w = 0.93$ cps @ 78.0°F $\sigma \doteq 43\ \frac{dynes}{cm}$

$\phi = 0.342$ $k = 778{,}000$ md

$$\therefore\ q = \frac{(3.5 \times 10^{-3})(43)(778{,}000 \times 0.342)^{\frac{1}{2}}}{0.93}$$

$$= 83.5\ \frac{barrels}{day} \cdot \frac{1}{ft}$$

$$= 152\ \frac{cm^3}{min} \cdot \frac{1}{cm}$$

ENCLOSURE 1 (Cont'd)

For a thickness of 1/2 inch (1.27 cm) the minimum throughput required would be:

$$q = 152 \times 1.27 = 193 \ \frac{\text{cm}^3}{\text{min}}$$

ENCLOSURE 2

Displacement Efficiency of Long Core

1 Atmospheric Pressure inches Hg	2 Upstream Pressure inches Hg	3 Pressure Disp. inches Hg	4 Saturation Pressure inches Hg	5 Production Prior to Flooding (Gas Saturation) cc	6 Production To Breakthrough cc	7 Cumulative Production to Breakthrough 5 + 6 cc
27.72	24.65	3.07	24.65	0	72.0	72.0
27.45	24.41	3.04	24.60	1.3	71.9	73.2
27.91	24.95	2.96	25.14	2.9	73.2	76.1
27.16	24.25	2.91	24.52	7.0	78.0	85.0
27.97	24.99	2.98	25.46	9.0	74.6	83.6
28.12	25.09	3.03	25.65	12.2	63.2	75.4
27.76	24.65	3.11	25.38	12.8	58.8	71.6
27.54	24.48	3.06	25.49	17.5	54.6	72.1
27.45	24.46	2.99	25.96	31.6	41.7	73.3
27.97	25.01	2.96	26.09	34.2	32.6	66.8
27.61	24.60	3.01	26.72	45.2	18.4	63.6
27.82	24.75	3.07	26.89	49.5	5.5	55.0
27.47	23.49	3.98	23.68	4.9	69.1	74.0
27.72	23.91	3.81	24.29	7.5	67.5	75.0

ENCLOSURE 3

Flooding Performance of Isolated Inverted Five-Spot

No Production Prior to Flooding

Total Production			Water Production	Oil Production			Producing
Increm.	Cumulat.	Displ. Pore Volumes	Incremental	Increm.	Cumulat.	Displ. Pore Volumes	W.O.R.
cc	cc		cc	cc	cc		
694	694	1.10	0 (B.T.)	694	694	1.10	0.00
508	1,202	1.91	125	383	1,077	1.71	0.326
508	1,710	2.72	125	383	1,460	2.32	0.326
584	2,294	3.65	187	397	1,857	2.95	0.471
644	2,938	4.67	262	382	2,239	3.56	0.685
799	3,737	5.94	408	391	2,630	4.18	1.043
682	4,419	7.03	380	302	2,932	4.66	1.258
740	5,159	8.21	481	259	3,191	5.07	1.858
859	6,018	9.58	597	262	3,453	5.49	2.28
852	6,870	10.92	674	178	3,631	5.77	3.78
739	7,609	12.10	622	117	3,748	5.96	5.32
830	8,439	13.41	717	113	3,861	6.14	6.35
819	9,258	14.72	737	82	3,943	6.27	9.00
781	10,039	15.96	713	68	4,011	6.38	10.50
787	10,826	17.21	736	51	4,062	6.46	14.42
1,081	11,907	18.92	1,024	57	4,119	6.55	17.98
794	12,701	20.19	762	32	4,151	6,60	23.80

ENCLOSURE 4

Flooding Performance of Isolated Inverted Five-Spot

Production Prior to Flooding =

219 cc = 0.348 Displaceable Pore Volumes

Total Production			Water Production	Oil Production			Producing
Increm.	Cumulat.	Displ. Pore Volumes	Incremental	Increm.	Cumulat.	Displ. Pore Volumes	W.O.R.
cc	cc		cc	cc	cc		
612	612	0.974	0 (B.T)	612	612	0.974	0.000
407	1,019	1.62	138	269	881	1.40	0.513
749	1,768	2.81	278	571	1,452	2.31	0.486
697	2,465	3.92	225	472	1,924	3.06	0.477
815	3,280	5.21	367	448	2,372	3.77	0.819
1,133	4,413	7.02	621	512	2,884	4.59	1.212
1,388	5,801	9.22	927	461	3,345	5.32	2.010
877	6,678	10.61	666	211	3,556	5.65	3.159
847	7,525	11.97	704	143	3,699	5.88	4.923
771	8,296	13.19	673	98	3,797	6.04	6.73
962	9,258	14.72	851	111	3,908	6.21	8.51
790	10,048	15.99	727	63	3,971	6.31	11.54
906	10,954	17.42	850	56	4,027	6.40	15.18
947	11,901	18.92	903	44	4,071	6.48	20.51
710	12,611	20.05	680	30	4,101	6.52	22.56

ENCLOSURE 5

Flooding Performance of Isolated Inverted Five-Spot

Production Prior to Flooding:

365 cc = 0.580 Displaceable Pore Volumes

Total Production			Water Production	Oil Production			Producing
Increm.	Cumulat.	Displ. Pore Volumes	Incremental	Increm.	Cumulat.	Displ. Pore Volumes	W.O.R.
cc	cc		cc	cc	cc		
470	470	0.746	0 (B.T.)	470	470	0.746	0.00
404	874	1.39	119	285	755	1.20	0.418
901	1,775	2.82	359	542	1,397	2.22	0.662
852	2,627	4.18	306	546	1,943	3.09	0.560
1,099	3,726	5.92	486	613	2,556	4.06	0.794
821	4,547	7.23	476	345	2,901	4.61	1.380
869	5,416	8.61	574	295	3,196	5.08	1.945
893	6,309	10.02	661	232	3,428	5.45	2.85
1,129	7,438	11.81	911	218	3,646	5.80	4.18
1,033	8,471	13.47	899	134	3,780	6.01	6.71
1,016	9,487	15.08	919	97	3,877	6.16	9.48
1,151	10,638	16.91	1,065	86	3,963	6.30	12.38
733	11,371	18.08	697	36	3,999	6.36	19.35
918	12,289	19.52	877	41	4,040	6.42	21.40

ENCLOSURE 6

Flooding Performance of Isolated Inverted Five-Spot

Production Prior to Flooding:

554 cc = 0.880 Displaceable Pore Volumes

Total Production			Water Production	Oil Production			Producing
Increm.	Cumulat.	Displ. Pore Volumes	Incremental	Increm.	Cumulat.	Displ. Pore Volumes	W.O.R.
cc	cc		cc	cc	cc		
237	237	0.377	0 (B.T.)	237	237	0.377	0.00
575	812	1.29	164	411	648	1.03	0.399
1,018	1,830	2.91	307	711	1,359	2.16	0.746
1,011	2,841	4.52	370	641	2,000	3.18	0.520
938	3,780	6.01	455	484	2,484	3.95	0.940
1,127	4,917	7.82	672	455	2,939	4.67	1.477
882	5,799	9.22	605	277	3,216	5.11	2.185
877	6,676	10.61	682	195	3,411	5.42	3.50
572	7,248	11.52	479	93	3,504	5.57	5.15
783	8,131	12.92	665	118	3,622	5.76	5.64
725	8,856	14.08	637	88	3,710	5.90	7.23
1,092	9,948	15.81	984	108	3,818	6.07	9.11
790	10,738	17.09	727	63	3,881	6.17	11.53
858	11,596	18.42	857	51	3,932	6.25	16.80

ENCLOSURE 7

Flooding Performance of Isolated Inverted Five-Spot

Production Prior to Flooding:

944 cc = 1.150 Displaceable Pore Volumes

Total Production			Water Production	Oil Production			Producing
Increm.	Cumulat.	Displ. Pore Volumes	Incremental	Increm.	Cumulat.	Displ. Pore Volumes	W.O.R.
cc	cc		cc	cc	cc		
158	158	0.251	0 (B.T.)	158	158	0.251	0.000
106	264	0.42	50	56	214	0.34	0.894
321	585	0.93	183	138	352	0.56	1.325
314	899	1.43	220	94	446	0.71	2.340
410	1,309	2.08	334	76	522	0.83	4.40
339	1,648	2.62	301	38	560	0.89	7.92
294	1,942	3.09	269	25	585	0.93	10.76
392	2,334	3.71	374	19	604	0.96	19.70
176	2,510	3.99	172	4	608	0.965	43.00
265	2,775	4.41	257	8	616	0.98	32.10
421	3,196	5.08	408	13	629	1.00	31.45
274	3,470	5.52	271	3	632	1.005	90.40

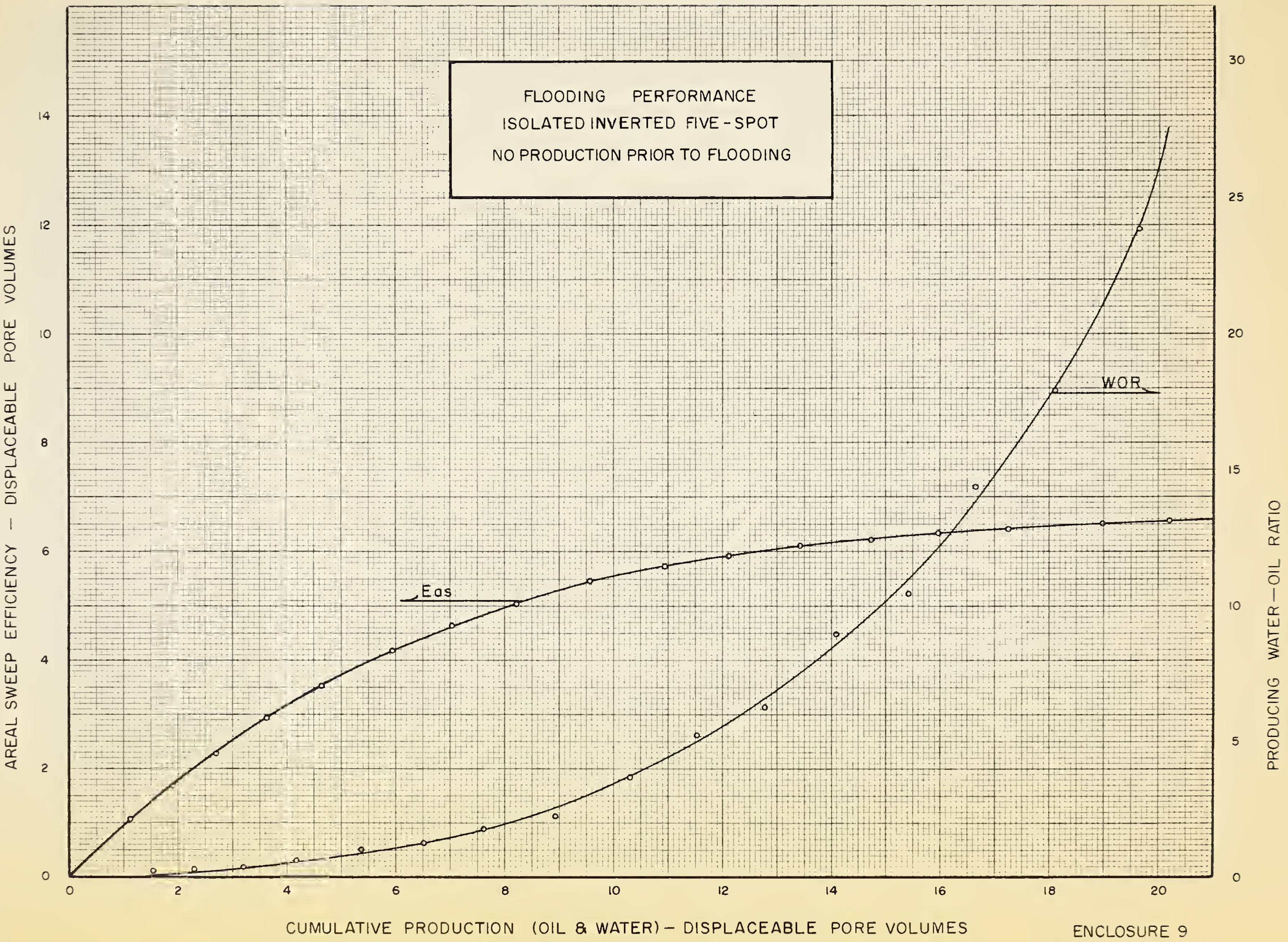
ENCLOSURE 8

Flooding Performance of Isolated Inverted Five-Spot

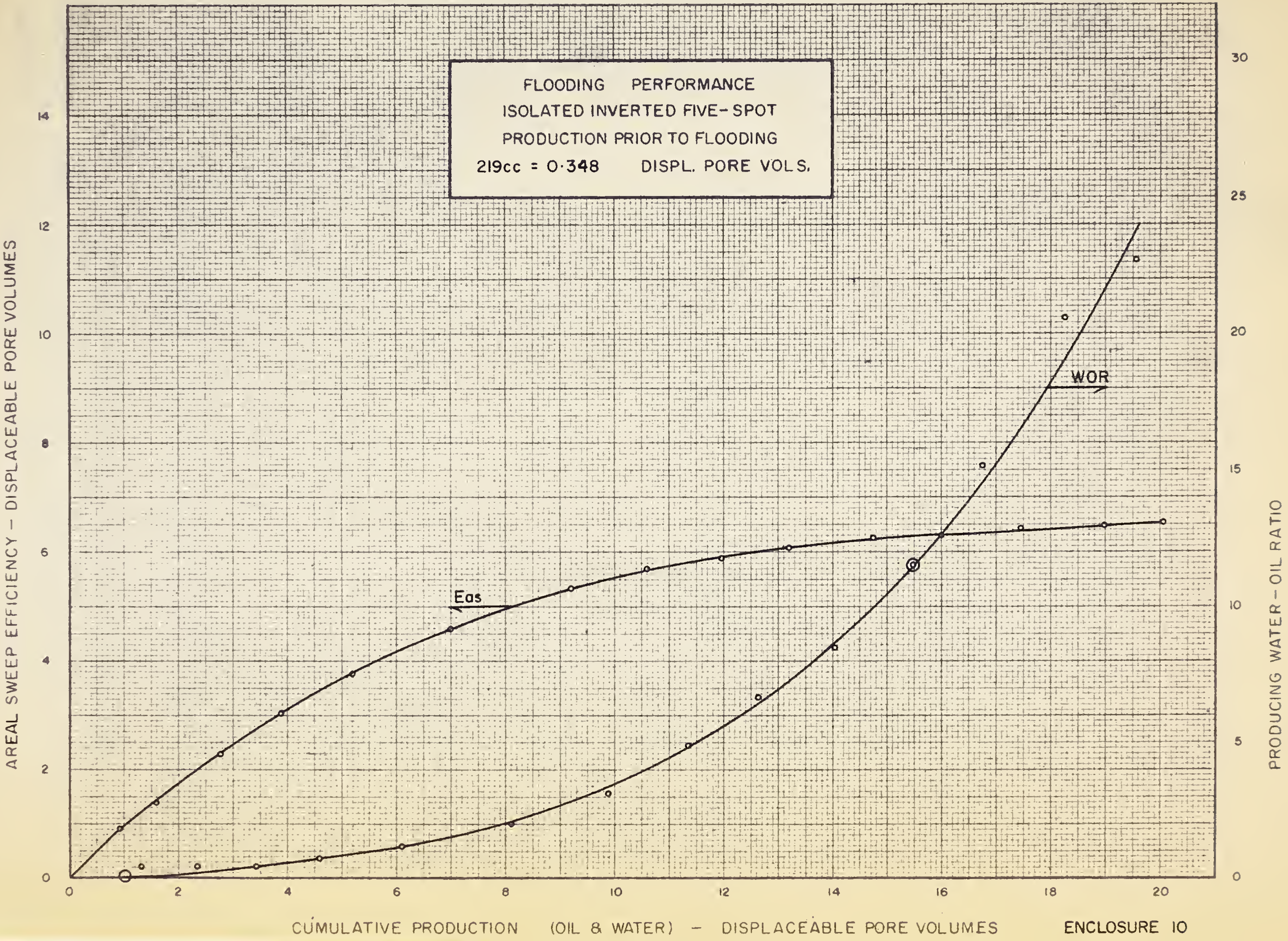
Production Prior to Flooding:

126 cc = 2.010 Displaceable Pore Volumes

Total Production			Water Production	Oil Production			Producing
Increm.	Cumulat.	Displ. Pore Volumes	Incremental	Increm.	Cumulat.	Displ. Pore Volumes	W.O.R.
cc	cc		cc	cc	cc		
133	133	0.212	0 (B.T.)	133	133	0.212	0.00
81	214	0.34	51	30	163	0.26	1.70
113	327	0.52	81	32	195	0.31	2.61
164	491	0.78	139	25	220	0.35	5.55
150	641	1.02	146	4	224	0.35	36.50
302	843	1.50	302	0	224	0.35	Infinite


FLOODING PERFORMANCE
ISOLATED INVERTED FIVE - SPOT
NO PRODUCTION PRIOR TO FLOODING
AREAL SWEEP EFFICIENCY — DISPLACEABLE PORE VOLUMES
0
2
4
6
8
10
12
14
PRODUCING WATER—OIL RATIO
0
5
10
15
20
25
30
CUMULATIVE PRODUCTION (OIL & WATER) – DISPLACEABLE PORE VOLUMES
0
2
4
6
8
10
12
14
16
18
20
Eas
WOR

ENCLOSURE 9



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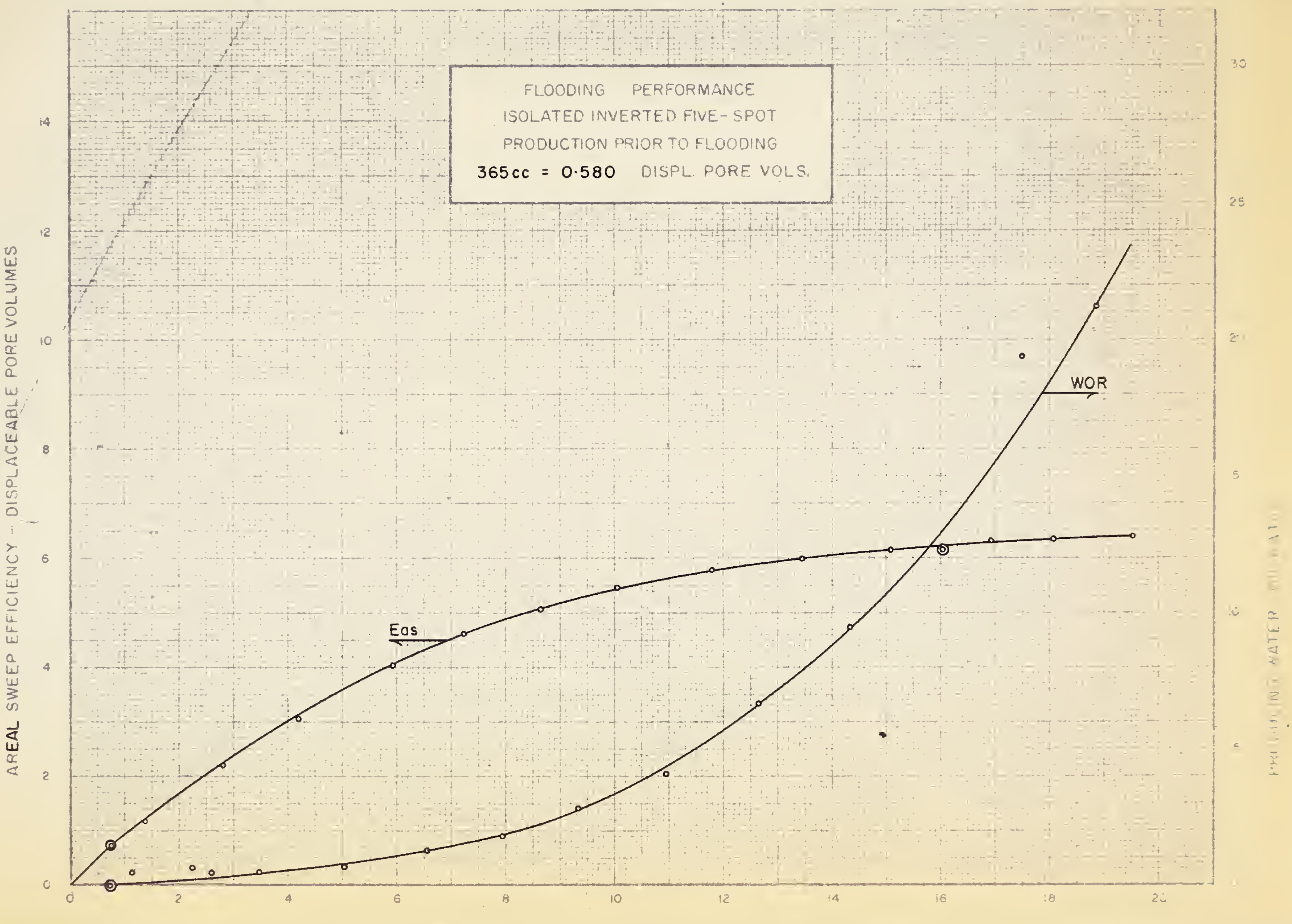

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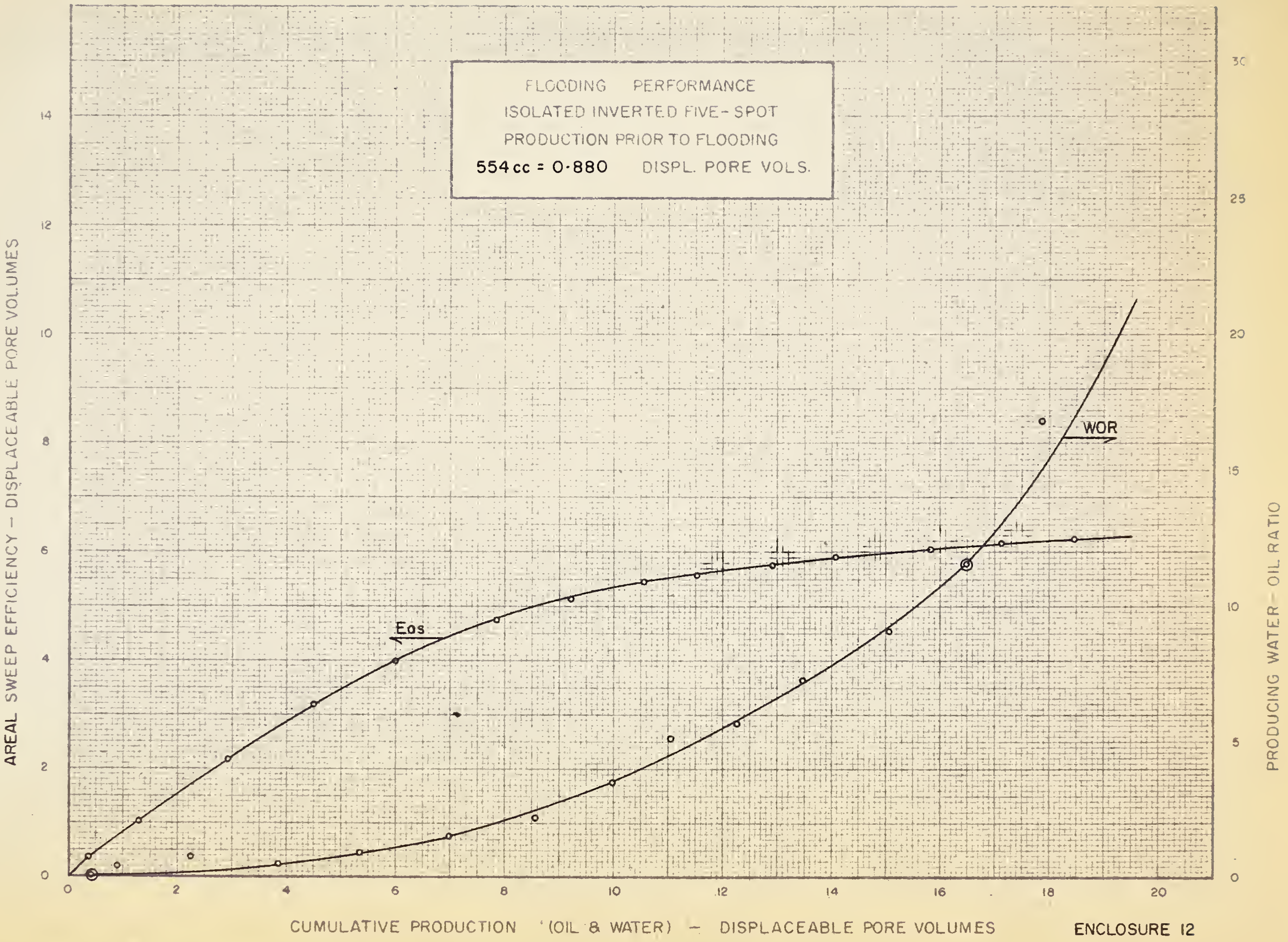
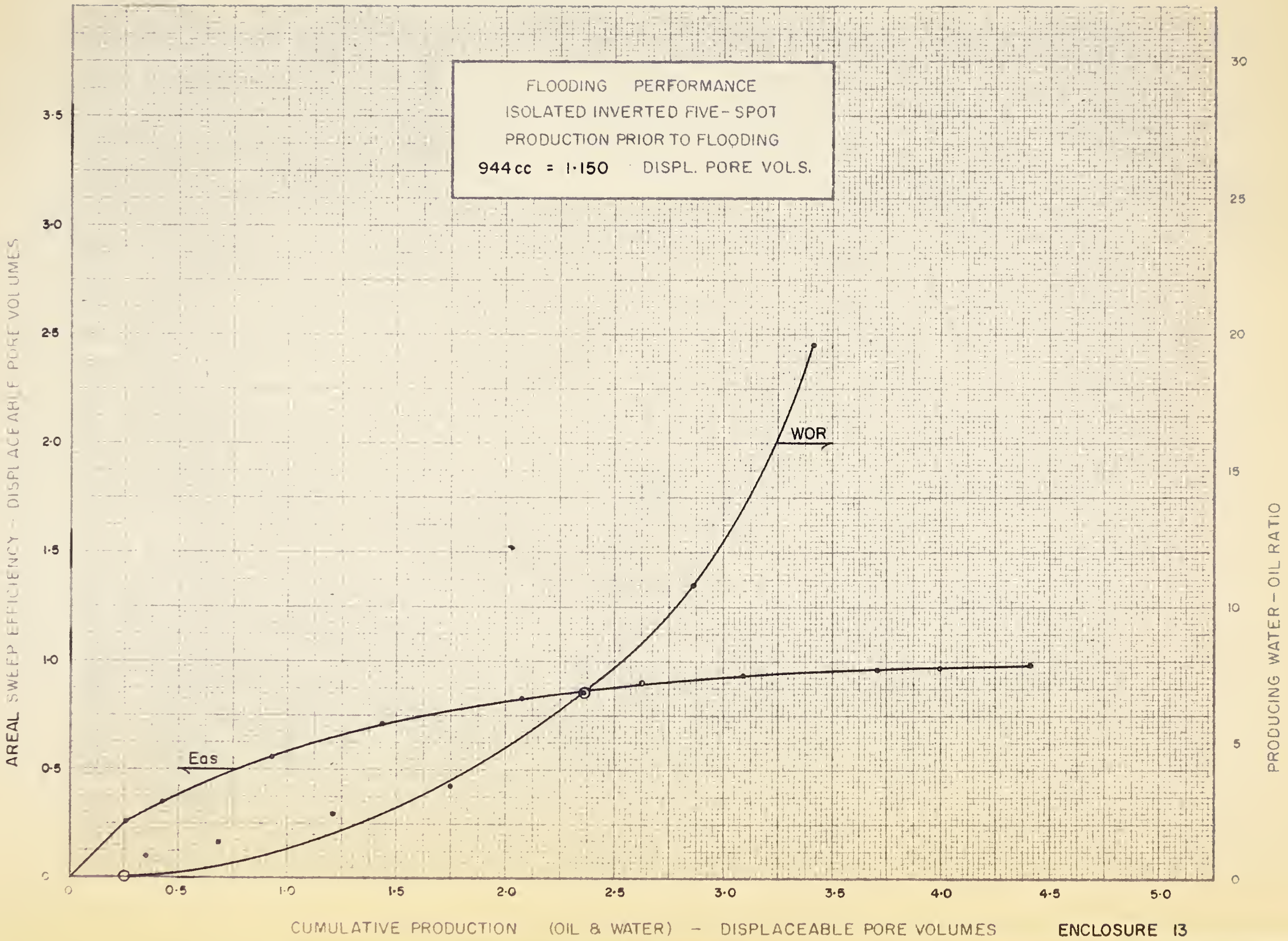
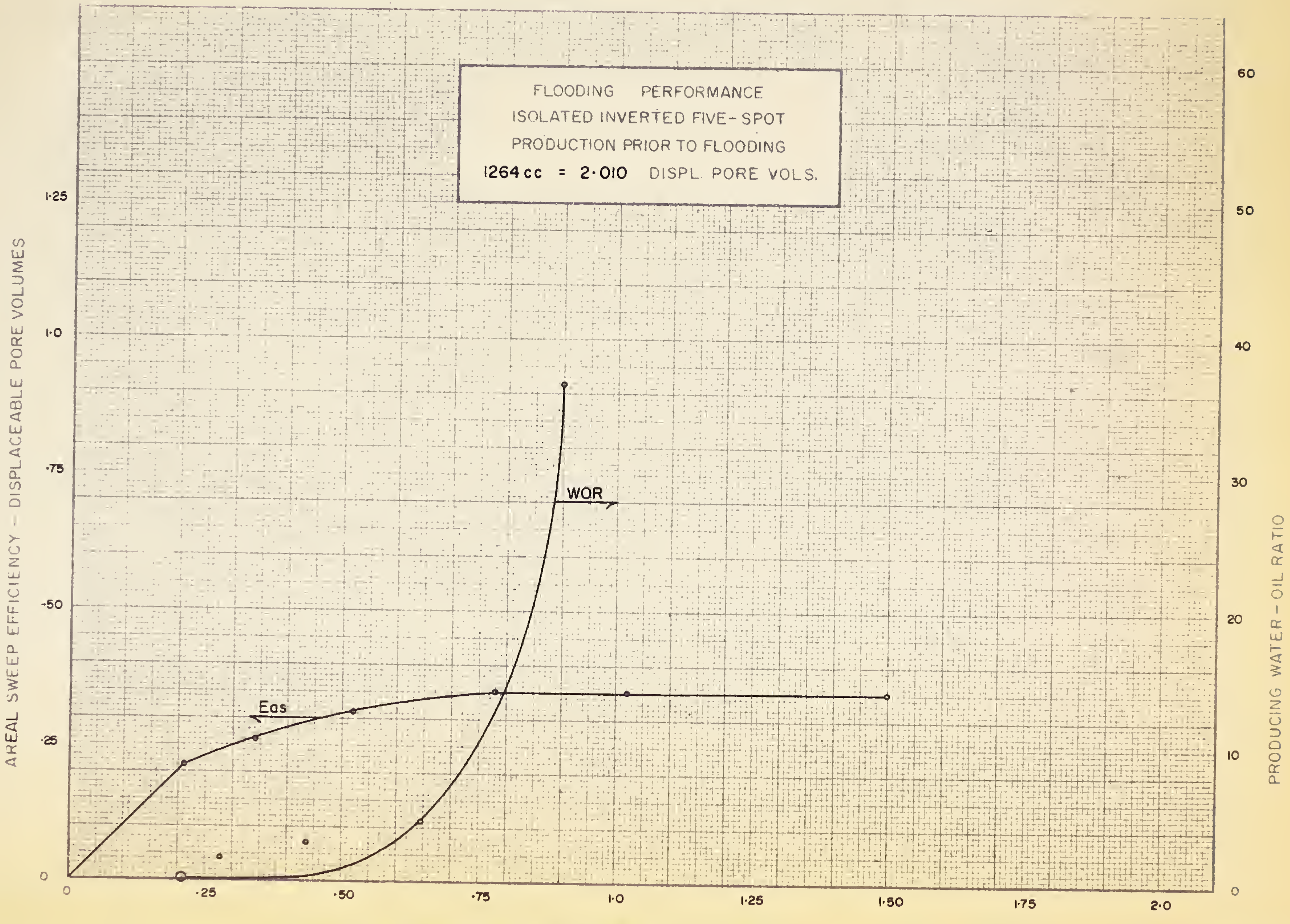


ENCLOSURE 12



ENCLOSURE 13



ENCLOSURE 14

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